Development of adjustable grazing incidence optics for Generation-X

Paul B. Reid[a†], Stephen S. Murray[a], Susan Trolier-McKinstry[b], Mark Freeman[a], Michael Juda[a], William Podgorski[a], Brian Ramsey[c], and Daniel Schwartz[a]
[a] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138
[b] Pennsylvania State University, 151 Material Research Laboratory, University Park, PA 16802
[c] NASA Marshall Space Flight Center, Huntsville, AL 35812

ABSTRACT

For X-ray astronomy, 0.1 arc-second imaging resolution will result in a significant advance in our understanding of the Universe. Similarly, the advent of low cost high performance X-ray mirrors will also increase the likelihood of more X-ray telescopes being funded and built. We discuss the development plans of two different types of adjustable grazing incidence optics: one being a tenth arc-second resolution bimorph mirror approach also suitable for extremely large collecting areas, and the second being a few arc-second radially adjustable mirror approach more suitable for modest sized telescopes. Bimorph mirrors will be developed using thin (0.1 – 0.4 mm) thermally formed glass or electroplated metal mirror segments with thin film piezo-electric actuators deposited directly on the mirror back surface. Mirror figure will be adjusted on-orbit. Radially adjustable mirrors will employ discreet radially electrostrictive actuators for mirror alignment and low spatial error frequency figure correction during assembly and alignment. In this paper we report on. In this paper we describe mirror design and our development plans for both mirror concepts.

Keywords: x-ray optics, adjustable optics, bimorph mirrors, Generation-X, Gen-X, WFXT

1. INTRODUCTION

For X-ray astronomy, 0.1 arc-second resolution with modest collecting area – several hundred to one thousand square centimeters, i.e., comparable to *Chandra* – will result in the opening of significant discovery space for bright objects such as the Crab, η Car, and Cen A. Potential observations could include bright regions of jets and knots in AGN, shocks and bubbles in galaxy clusters, inner regions of nearby BH accretion, and the inner regions of the Crab nebula. A tenth arc-sec large X-ray telescope in space with ten to fifty square meters collecting area could observe the formation of the first galaxies and black holes in the Universe. In fact, NASA has awarded and funded an Advanced Mission Concept Study program for such a mission, the "Generation-X" (*Gen-X*) observatory. This observatory will have an effective area of ~ 50 m^2, 500 times that of the current *Chandra X-ray Observatory*, but with 0.1 arc second angular resolution, several times better than *Chandra*. (A discussion of Generation-X astrophysics is found in reference 1). Meeting the combined challenge of large area and ultra-high angular resolution will require breakthroughs in technology for X-ray telescopes. Realizing *Gen-X* within the Orion launch vehicle payload limits requires very lightweight optics and hence thin (≤0.2 – 0.4mm) mirrors. To achieve the demanding sub-arc second angular resolution with such lightweight optics, Gen-X is envisioned to require adjustable grazing incidence mirrors[2-4].

Implementing adjustable grazing-incidence X-ray optics brings unique challenges. No astronomical X-ray telescope has used active optics. Our investigation will employ two different types of adjustable mirrors:

† email: preid@cfa.harvard.edu, phone: 1-617-495-7233, fax: 1-617-495-7356

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deformable bimorph mirror technology[4], and radially adjusted mirrors[5]. We consider these mirrors adjustable rather than active, which are continuously active during an observation. In our approach, the mirror figure is corrected once on-orbit, or very infrequently, to achieve desired figure levels that could not be achieved, maintained, and/or measured on the ground.

In this paper we describe our investigation approach. We will use either thermally formed glass mirror segments or electroformed metal mirrors (segments and shells). In the bimorph mirror approach, thin piezo-electric material is directly deposited on the back surface of the mirror. Energizing the actuators will be used to locally correct the mirror figure without the need for a reaction structure. Such optics would be adjusted only once (or very infrequently) - during an on-orbit calibration to remove figure errors that could not be measured accurately enough on the ground. Prior work on Generation-X[2,3] has suggested that, with good mirror roughness and adjustment of figure errors with spatial periods longer than 30 – 40 mm, the 0.1 arc-sec goal can be achieved. These grazing incidence mirrors will be segments like those on Constellation-X; that is, not full shells of revolution, but only an approximately 10 to 30 degree section of a shell.

In the radially adjustable mirror approach[5], electro-restrictive actuators are arrayed radially and axially between mirror shells. A central core serves as the innermost shell's reaction structure. Radial displacements are used to correct low order axial and azimuthal figure errors – the type that will dominate the image core.

2. DESCRIPTION

2.1. Bimorph mirrors for 0.1 arc-sec resolution

Achieving 0.1 arc-sec resolution via figure correction with actuators has been analytically shown feasible[2,3]. In Figure 1 we plot on a log-log scale axial mirror figure error PSDs for Con-X goals, Chandra, and Gen-X before and after piezo figure correction ('adjustment'). The axial extent of the piezo cells was 20 mm. Figure 2 shows an encircled energy curve at 1 keV with 0.1 arc-sec half power diameter, predicted from the post-adjustment Gen-X PSD in Fig. 1. (Both figures from ref. 2).

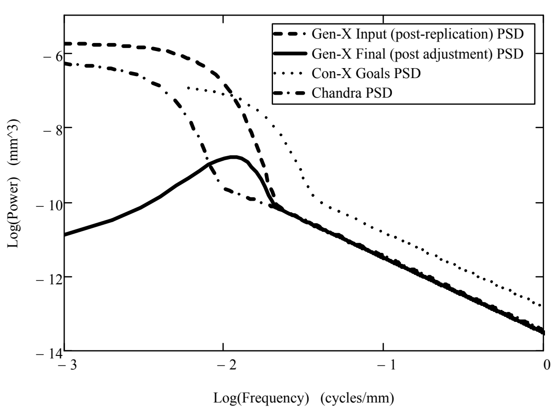


Figure 1: PSDs (see text)

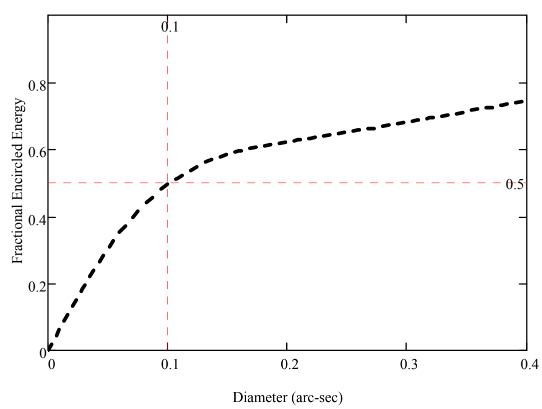
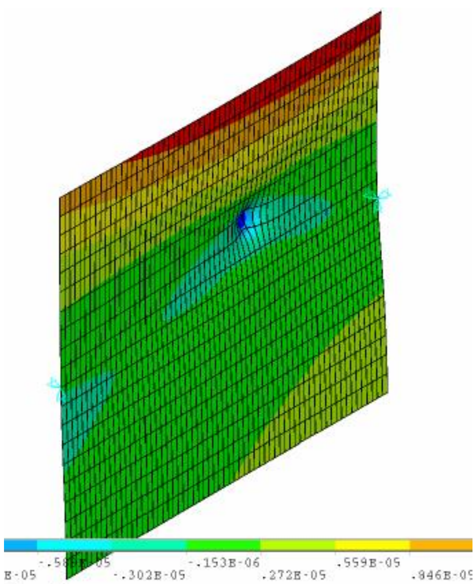


Figure 2: Encircled energy at 1 keV

Our approach to developing 0.1 arc-sec, lightweight, adjustable grazing incidence mirrors is to start with 400 μm-thick thermally formed borosilicate glass mirror segments, directly deposit thin (~5 μm thick) piezo-electric material on the back surface of the mirror segment, and then deposit a "pixelated" array of electrodes on the piezo material to form an array of piezo cells. As a voltage is applied across a mirror electrode and one of the back surface electrodes, strain in the piezo, parallel to the mirror surface, introduces local bending in the mirror due to the differential expansion or contraction of the two layers – mirror substrate and piezo. This locally deforms the mirror. By controlling the form of the deformation to match the local figure errors in the mirror, we seek to correct figure errors in mirrors to a level not achievable by ordinary means.

For the above approach, glass mirrors are used for proof-of-concept. Metal replicated mirrors may also be tried. We choose segmented mirrors for several reasons. Because of full shell "hoop" stresses, deformations introduced in one part of the mirror may be reflected in another, remote, part of the mirror. This greatly compromises the efficacy of an optimization and makes full shell mirrors a poor choice for this type of adjustable grazing incidence mirrors. As an additional reason, the desire to have large collecting area drives one to relatively large focal lengths and large mirror diameters (e.g., 50 - 60 meters and 8–16 meters, respectively, on Gen-X). Full shells are impractical for such large mirror sizes. We envision eventually using segments as large as 1 m x 1 m, which implies an angular span of ~ 10 degrees for a 12 m diameter telescope. The mirror segments will be supported kinematically at either their ends or corners. (This will be explored as part of our finite element analyses). Mirror segments will be divided into a set of piezo cells, with the azimuthal extent of the cells larger than the axial extent. This is because x-ray performance is much less sensitive to azimuthal errors, and our desire is to correct a wider bandwidth of axial figure errors. For development purposes we will use axial piezo cell sizes of the order of ~ 10 - 20 mm, with azimuthal extent of 20 – 50 mm. (At this point in time, Gen-X considerations imply ~ 20 mm axial by ~ 50 – 100 mm azimuthal piezo cell sizes). Holding a small angular span segment (with a relatively large radius of curvature) kinematically at two edges, deformations due to strain in a single piezo cell are localized. This is seen in Figure 3, where the results of finite element modeling for a Gen-X sized mirror (1 m x 1 m) segment is shown. In Figure 3, an ~ 6 parts per million strain was applied to a single piezo cell near the center of the mirror, producing the localized deformation seen in darker blue.



With localized deformations, it is possible to model and measure the deformations as a function of strain and piezo location, determining a set of influence functions. With these, calculating the required sets of piezo voltages to correct mirror figure error becomes a 2-dimension deconvolution, or optimization, problem. Such effects as crosstalk, cell size and shape, can dramatically affect the quality of the optimization, and so these will be a focus of our investigations. In addition, piezo cell size will affect the spatial frequency bandwidth of correctable figure errors, so this too is a consideration. (Note, an axial, 1-d, optimization is also possible as is used for synchrotron mirrors, but in general results in poorer performance.

Figure 3: FEM simulation of segment response to strain in an individual piezo cell.

In the following sections, we describe our approach in more detail.

2.1.1 Bimorph Adjustable Optics Technology Requirements

Active, or adjustable, figure control of optical mirrors is an established method for improving the performance of astronomical telescopes and other optical systems[6-8]. Active and adaptive optics systems have been developed for many modern ground-based astronomical telescopes[9,10] and have been developed into a commercial enterprise by companies such as Xinetics, Inc. While we build upon the knowledge and technology developments from suitable optical telescopes[11,12], we note the significant differences between design drivers for adjustable optics in X-ray and optical telescopes:

- The ratio of optic surface area to effective area for grazing incidence X-ray telescopes is 100 times larger than for normal incidence optical telescopes. Furthermore, optical telescopes typically have secondary and even tertiary reflecting surfaces in the imaging path which are much smaller than the primary reflector. This allows active technologies to be implemented on small scales with dense packing of actuators, such as arrays of discrete micro-electromechanical (MEM) devices, derived from advances in the semiconductor industry. In Wolter I type x-ray telescopes, adjustment control must be directly applied to the large area of the mirrors.
- Optical telescopes often have arbitrary amounts of volume behind mirrors to install actuators and support structure. In grazing incidence X-ray telescopes, mirrors are typically densely packed to produce reasonable effective area. This strongly limits the allowable thickness of reaction structures on each mirror and prevents the use of an extensive rigid support structure which would obscure the X-ray light path.

A low power, low mass, thin adjustment method is needed, with a manufacturing process that can be readily scaled to very large surface areas. *Gen-X* will require perhaps 10^6 to 10^7 separate actuation regions, so we also seek an adjustment technology with reliable, robust and stable actuation control. We will not be able to perform a system-level calibration of an assembled telescope before launch due to its size and flexibility under gravity, so we must design an adjustment technology that provides good performance predictability. Mirror segments will be manufactured with a figure close to the desired shape, so the technology must be applicable to pre-curved optics.

2.1.2. On-orbit figure correction with bimorph mirrors

Figure correction on-orbit can be accomplished by a variety of means[3,4]. A robust technique makes use of the Hartmann test[13], in which a pencil beam illuminates a portion of the optical system. Typically, the beam can illuminate an array of pinholes on the entrance aperture. Alternatively, as we envision it, the beam can be made to originate from the system focus and illuminate the optical system from the "back" end. Using a retro-reflector at the front of the optical system, the pencil beam is made to traverse the optical system twice, returning to the focal plane with double the sensitivity. By precisely measuring where the returning beam intersects the focal plane, and knowing what part of the optical system was illuminated by the beam, one can determine the local ray deviation for that part of the optical system (for a set of mirrors, this is the equivalent local slope error). By illuminating in turn many different parts of the mirrors, one can reconstruct the figure errors of the optical system. In a sense, the Hartmann test is an experimental application of ray-tracing. (This test was used to align and focus the 8 different mirrors of the Chandra Observatory, using the AXAF Centroid Detector Assembly [CDA]). In our case, a similar system can be mounted on the spacecraft. Using precision mirrored forward aperture doors as retro-reflectors, and a smaller sized 'Hartmann' beam than on Chandra, each mirror segment in the optical system can be aligned and their figure corrected. By using a small enough pencil beam, sufficient axial resolution can be achieved to also correct the lowest order axial figure error. This alignment and figure correction approach will be relatively rapid and is highly convergent. Final calibration using bright cosmic X-ray sources might still be necessary to achieve optimum imaging performance, but starting from near final figure, this will greatly reduce the time required for a celestial-based calibration . We expect that a benign thermal environment at L2 would allow weeks or months between refiguring calibrations.

2.1.3. Bimorph deformable mirror description

For the highest angular resolution goals we use a low-profile deformable mirror, or "bimorph" mirror[6], where differential strain between two layers of material in the mirror causes localized two-dimensional curvature change (see Figure 4). Deformable mirrors have been manufactured over the past decade that utilize small, adhesively bonded piezoelectric ceramic elements. Our concept is to deposit piezoelectric or other strain-inducing materials directly on the non-reflecting [back] surface of the mirror elements as a thin film, together with upper and lower electrode layers. The thin layer of piezoelectric material, with the required electrodes, can be deposited with different thicknesses and geometries through masking and/or etching techniques to provide localized strain and curvature control on multi-cm scales. In this work, as in many piezoelectric micro-electromechanical systems, deflection of the mirror surface hinges on a large $e_{31,f}$ piezo coefficient, so that a small voltage applied across the thickness of the piezoelectric film results in an in-plane stress, and hence deflection[14].

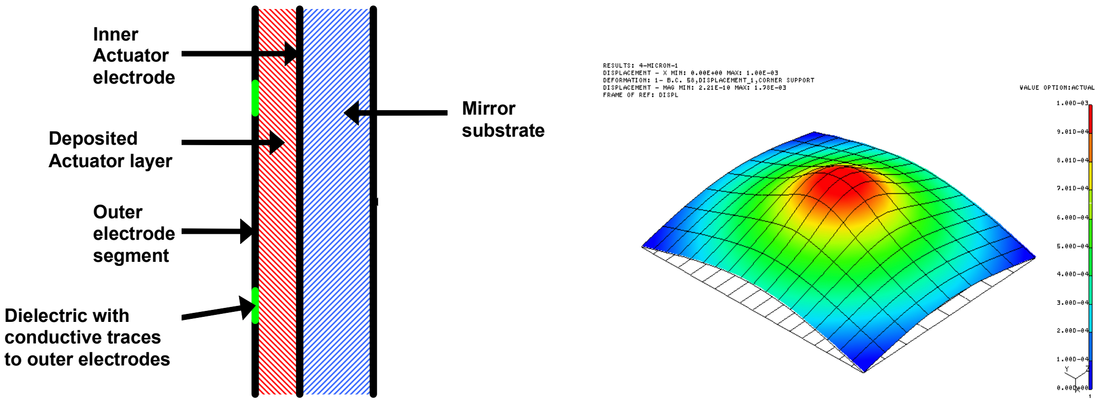


Figure 4. Left: Cross-section of proposed bimorph construction. Right: Finite-element model of a 10 x 10cm^2 bimorph surface with a 1 µm deformation induced by uniform strain over the central 3cm x 3cm of the surface.

Lead zirconate titanate (PZT) offers considerable advantages, as it has a far larger piezo-electric coefficient than can be achieved in alternative piezoelectric materials such as AlN or ZnO. One of the most significant challenges is the need to integrate the piezoelectric film directly on the mirror, rather than a Si substrate, without inducing uncontrolled curvatures due to thermal expansion mismatches. It is important to note that neither silicate glass nor metal alloys are thermodynamically stable in contact with PZT. To avoid reactions a Pt bottom electrode with a Ti adhesion layer will be employed. This has been shown to enable phase-pure perovskite thin films on comparable substrates[15,16].

Two PZT compositions will be explored. The first, $PbZr_{0.52}Ti_{0.48}O_3$ (PZT 52/48), is at the morphotropic phase boundary where the piezoelectric coefficients are maximized (Figure 5)[14], but for which the crystallization temperatures are typically higher. Indeed, in many MEMS applications, the piezoelectric coefficient is optimized for crystallization temperatures of 650 – 750°C. While it has been demonstrated that far lower substrate temperatures can be employed if the surface his heated (e.g. via laser annealing)[16], the approach is not readily scaled to the large areas ultimately desired for grazing incidence adjustable mirrors. Initial work on this composition will focus on optimizing the processing on the mirror blanks and characterizing the piezo coefficient response that can be achieved at temperatures that do not lead to excessive deformation. The second composition to be explored is $PbZr_{0.2}Ti_{0.8}O_3$, PZT20/80. While this will result in some loss of piezoelectric coefficient due to the distance from the morphotropic phase boundary, it should offer both a reduction in processing temperature and lower residual stress that could change mirror figure.

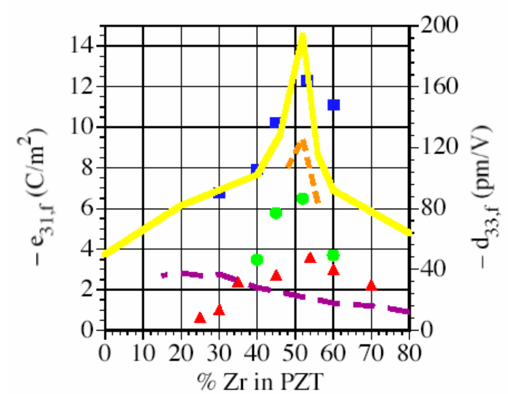


Figure 5: Composition dependence of the relative piezoelectric response in PZT thin films. Symbols are for $e_{31,f}$ data, lines are for $d_{33,f}$ data (ref. 15)

As part of the piezo material investigation, we will also examine process dependencies. Thermally formed borosilicate glass mirror segments are being used, with a transition temperature of ~ 557C. Thus, we can trade between piezo materials with crystallization and annealing temperatures lower than 550C, where the piezo is deposited post-thermal forming, and with materials with significantly higher crystallization temperatures, where the deposition is before thermal forming. In both cases we will clearly need to be concerned with material delamination and crazing due to the CTE mismatch, so this represents another criteria for success besides final bimorph mirror deformations due to piezo deposition.

Two different processing methods will be investigated: chemical solution deposition (CSD) and sputtering. Initial CSD work will be conducted on flat substrates using spin coating of the solutions in order to prepare films with well-defined thickness values. Curved surfaces will be coated either via dip-coating of sols or sputtering, depending on results of optimization studies.

Use of bimorph mirrors eliminates the need for a rigid backplane structure. Mirror segments will be attached kinematically to their support structure at the segment corners or two sides so as to enable rigid body adjustment of each optic in the assembled telescope. Our proposed lightweight bimorph technology may also be applicable to space-based optical and infrared mirrors, such as needed to image Earth-like planets.

2.1.4. Bimorph mirror development plan

The goals of our program are (i) to develop the technology for figure control of future X-ray telescopes, (ii) to design, manufacture, test, and characterize the control of sample mirrors with active figure control. We split our work into stages which include requirements generation, concept development and modeling, and fabrication and test. Our program will demonstrate surface figure control of a mirror sample to ~ 5 nm rms, which is equivalent to ~0.1 arc-second half-power diameter point response performance for an X-ray telescope. This performance will be demonstrated using both optical metrology and x-ray testing. Our baseline mirror segment size for the technology demonstration at the end of the program is ~ 20cm x 20cm (comparable in size to a number of Constellation-X segments). The mirror back surface will be covered with an actuator control grid consistent with control length scales needed for ~0.1 to 0.2 mm thick mirrors and that can demonstrate scalability to the large mirror areas needed for Gen-X.

The program stages are described below:

- Derive primary performance requirements for adjustable optic figure control from expected X-ray telescope performance requirements and expected mirror substrate manufacturing specifications. Primary performance parameters are: adjuster grid geometry and spacing, adjustment range, and accuracy. The approach is to develop the ability to adjust and control low and mid spatial frequency figure errors. We will perform a geometric calculation to budget the allowed errors, and then simulate and ray-trace a mirror generated with those parameters in order to iterate the requirements. Mirror parameters will include axial figure errors as a function of spatial error frequency (the axial figure error power spectral density), and azimuthal errors (average radius, cone angle, meridionally varying tilt, or $\Delta\Delta r$, and meridionally varying piston, or roundness). The primary output of this study is to determine the size of the actuators required for mirror control. Actuator size directly impacts both the required "starting" (pre-adjustment) figure and the final (post-adjustment) figure. Preliminary investigations as part of the Gen-X Visions Mission Study indicate that actuator axial size of 1 – 2 cm is required[2]. Because of the scope of this investigation, we will not define actuator requirements in areas of mission architecture and systems engineering (such as operating temperature and tolerances, the duty cycle and power requirements for control actuation, the accessibility to establish the electrical connections, reliability and redundancy, etc.). Such considerations are more suitably the subject of a mission specific investigation.
- Perform detailed finite element and ray trace modeling to characterize the mirror response and adjuster influence functions of candidate adjuster plus optic configurations. This modeling is used to refine the requirements for the adjuster, interpret data from laboratory measurements and refine adjuster control algorithms. We will explore the deformation introduced by unit strain (the influence function) as a function of piezo cell location on the mirror, cell size, and cell shape. Cell size, and the shape of the influence function, will play critical roles in the frequency content which can be corrected by adjustment.
- Develop piezo materials and deposition processes that provide the necessary strain/thickness and are compatible with the mirror substrate materials, as described in Section 2.1.3.

- Manufacture and characterize optic samples. We will initially use either flat glass or electrolytic Ni/Co mirrors (prepared by the NASA Marshall Space Flight Center). Sample sizes up to 12.5cm long will be used, approximately 0.1 – 0.4 mm thick. A Pt electrode will be deposited on the back side of the mirror, followed by several microns of a piezo material such as lead zirconate titanate, followed by a segmented set of electrodes and control leads. Pre-piezo deposition metrology will be performed via optical interferometry and mechanical profilometry.
- Following delivery of the test optics with integrated piezo material, optical interferometry and mechanical profilometry will be used to measure the post-deposition figure and to measure the figure control response of the test optic. Multiple optical interferograms will be collected and analyzed to characterize individual actuator responses and determine joint adjuster responses in the form of a multi-dimensional response matrix. Finite element models will be updated to better fit reality. We will explore:
    - deformation of the substrate as a result of piezo deposition,
    - cross-talk between adjacent piezo cells,
    - measure linearity and hysteresis of piezo response, and
    - measure the influence functions of the various piezo cells.

  This last part of the investigation will be used to determine optimal shapes for the piezo cells. This step of the investigation will be iterative as we learn about the process and the adjustment functionality, feeding that information back for modification of the piezo-electric material and cells.

Optical testing will consist of a baseline measurement of the optic, followed by an adjustment of optic figure using the adjusters, and then re-measurement of the figure. The test plan will include a series of actuator adjustments designed to enable us to compare actual figure change with predicted (modeled) figure change. Ultimately, optical testing will include a demonstration of figure control by producing desired complex changes in figure and verification of those changes with the differential metrology. Note that using differential measurements as described above will improve our ability to characterize actuator adjustments and compare with models. This is because making such relative measurements is insensitive to the absolute calibration and systematic errors of the interferometers, relying solely upon their repeatability (which can be better than a nm, rms).

- Upon completing our investigation with flat mirror substrates, we will move on to conical mirror substrates. Using existing shell mandrels with and without masking, will enable MSFC to produce either full shells or mirror segments. The deposition process will be modified to use curved substrates and incorporate lessons learned from the flat substrates. The segments will be tested with optical normal incidence interferometry, as before with the flat segments. The conical mirrors will also be tested in x-rays at the MSFC stray light facility.
- Examine feasibility of figure correction via on-orbit Hartmann testing. This activity will focus on the correction limits of Hartmann testing, not on logistics such as power, mass, cost, etc. We will determine what spatial error frequency content and slope error we believe this approach is amenable to, using that information as an input to reasonable mirror design.

2.2. Radially adjustable mirrors

Radially adjustable grazing incidence mirrors are not anticipated to be tenth arc-second resolution optics. They are however, a potentially low cost approach to significantly improve imaging resolution of existing technology thin mirrors to the few arc-sec level for moderate effective area missions. These mirror assemblies will consist of a precision lightweight cylindrical or conical core (perhaps graphite epoxy or silicon carbide) to the outside of which is attached a set of axial rows of electrostrictive actuators[5]. The core serves the purpose of the reaction structure in a conventional active mirror. Each axial row is aligned along a different azimuthal position, as shown in Figure 6. The adjusters are glued to the core and then the innermost mirror shell (or segment) is glued to the adjusters.

After curing, mirror alignment and low frequency axial and azimuthal errors are corrected by energizing the adjusters appropriately which causes their radial length to expand or contract relative to a nominal radial dimension. Bi-directional adjustment is accomplished by first biasing all the adjusters to their approximate midpoints, so that increased or decreased voltage results in displacements with are radially out or radially in, respectively. The Hartmann test, described in Section 2.1.2, is used as the adjustment metrology. After alignment/adjustment of the first shell or set of segments, the next set of adjusters are glued to the back side of the

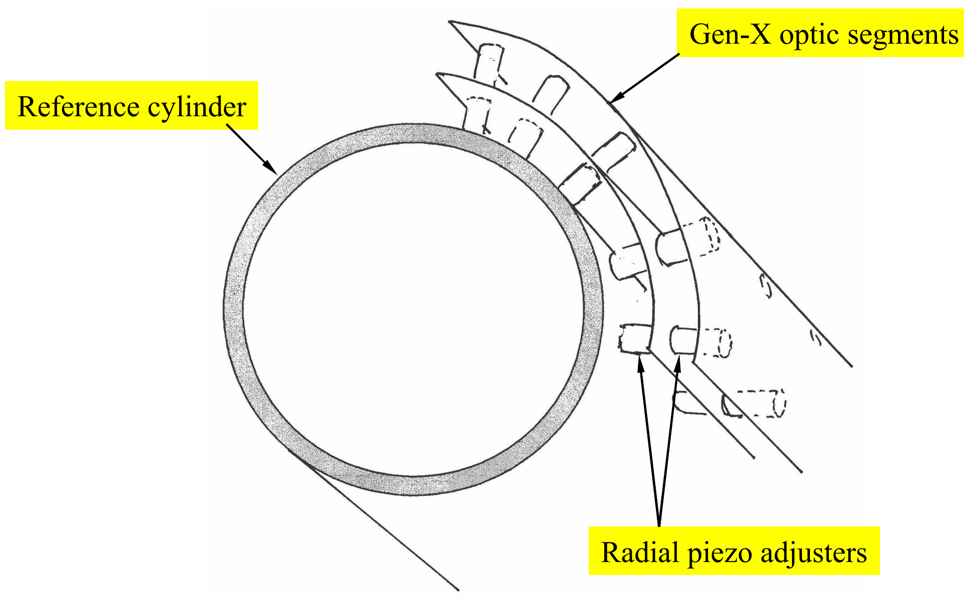


Figure 6: Radially adjustable mirror assembly

mirror shell in place, the next mirror shell is glued to the adjustment, and alignment and figure correction is made using the Hartmann test for the second shell with the second row of adjusters. The process repeats itself until all the mirrors are successfully mounted, aligned, and have their lowest order figure corrected. This process should result in a relatively robust structure which has corrected the lowest order figure errors such as axial tilts and sags, and several orders of azimuthal roundness errors such as delta-delta-radius (azimuthally varying cone angle error). In addition, by positioning the mirror segment or shell at the correct radial position and adjusting to the appropriate cone angle, the mirror pairs will be aligned confocal at the same time.

Our development activities for this adjustable mirror approach will also start with adjustment of flat sheets of borosilicate glass thermally formed flat. An M x N array of adjusters will be mounted to a thick plate reaction structure, and then the flat glass glued to the adjusters. The entire assembly will be held such that the mirror normal is horizontal, minimizing deformations due to gravity. Mechanical profilometry and optical interferometry will be used to measure mirror figure and adjuster influence functions. Comparisons will be made between the experimental data and finite element models of the system, and the models will be updated. We will then design a system for full shell electro-formed Ni/Co mirrors produced by MSFC, which will be tested in x-rays.

We envision this type of adjustable grazing incidence mirror most useful for moderate or smaller area missions, as the cost of adjusters and applying them to the mirrors may get prohibitively expensive for a mission such as Gen-X. On the other hand, more modest sized missions such as WFXT, using Ni/Co shells, may be ideally suited for such an application.

Eventually, we will wish to test the ability of the system to respond to actuation once it is fully built-up and bonded. One can imagine that given the potential stiffness of the structure, it will be necessary to drive sets of actuators at one time so as to avoid the introduction of large stresses. It will necessary to test this experimentally.

While not necessary for the development and construction of a telescope, such a capability would be extremely useful to correct for on-orbit performance changes, or perhaps even modifying mirror prescription on-orbit between e.g. Wolter-I and wide-field prescriptions such as polynomial representations[17]. The ability to change back and forth between both designs would enable a single mission to serve both as a wide field survey telescope and a high resolution narrow field imaging telescope.

3. SUMMARY

Two different types of adjustable grazing incidence mirrors have been described, and our technical development plans presented, each satisfying a different need in astronomical x-ray telescopes. The design of and development plans for bimorph mirrors were described. These mirrors are comprised of thin glass or metal substrates with a thin film piezo electric directly deposited to the mirror back surface. Strain applied parallel to the mirror surface produces localized bending of the mirror. These actuators will be used on-orbit to correct mirror figure and achieve tenth arc-second imaging resolution. The design and development of a radially adjustable grazing incidence mirror was also described. This telescope concept will use adjusters with their strain in the radial direction. They will be used to align metal shell mirrors and to correct low frequency axial and azimuthal errors during assembly and alignment.

4. ACKNOWLEDGEMENTS

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